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Registered Oblique EO Imagery and Synthetic Aperture Radar (SAR)

Timothy M. Payne

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Timothy M. Payne

Land, Space and Optoelectronics Division
Electronics and Surveillance Research Laboratory

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ABSTRACT

The process of registering oblique EO imagery simultaneously acquired from the same platform as a SAR image is reported along with the usefulness of such information. The geometry of the images is different, and the process of warping the oblique EO image to the nadir or plan map type view of the SAR leads to information about elevations within the scene which cannot be obtained from either of the individual sensors without the inclusion of either prior knowledge of the scene or recognition capabilities.

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EXECUTIVE SUMMARY

Long range oblique Electro-Optic (EO) images, such as those taken from the side of an aircraft, provide pictures which we can generally recognise. Unfortunately the geometry of this imaging process makes it difficult to determine the relative position of objects in terms of range since the scale of the image varies as objects become more remote. Unless the objects in a scene can be identified and the relative scales computed from knowledge of their actual size, then it is not possible to determine the relative positions of objects within a scene.

Airborne Synthetic Aperture Radar (SAR) provides an image in all weather conditions. Objects within the image are easily located since the image has the same geometry as a topographic map; however the resolution of the SAR image is less than that obtainable with an EO sensor and recognition is generally more difficult. It is possible to register the EO image with a plan map instead of a SAR; however it is not envisaged that the approaches presented in this paper will be used on regions where this type of information is available, so the fusion of plan maps and oblique imagery will not be discussed.

By warping the EO image to align with the SAR image the advantages of the EO image, with regard to feature recognition, are retained, while the relative location of features is simplified since the image now has a geometry similar to a topographic map. In the process of warping the EO image, information about the elevation and structure of features within the image are obtained. This elevation information cannot be directly obtained with either of the sensors individually. Unfortunately the matching process between images is difficult to perform automatically. In some special cases it may be possible to determine the size of an object from an EO image using either the shadow or knowledge of the size of other objects in the scene; however it is impossible to determine the elevation at which the object exists without the additional

information available from a second sensor which has a different perspective view of the scene.

This report outlines the procedures involved in warping an oblique EO image to a SAR image and discusses the merits of this procedure. Automation of the elevation extraction procedure is also discussed and a simple simulation is performed to demonstrate its usefulness. Unfortunately the real SAR information that was available was of an extremely poor quality due to a failure in the equipment and no additional trials were able to be performed. The existing real images did indicate that some additional assumptions would be required to enable processing to occur automatically- the nature of these assumptions will vary depending on the nature of the scene and it was believed that advice should be sought regarding the application of the approach before further work should occur using what might turn out to be invalid assumptions about the image type. The simulated scenes represent scenes which would require very few or simple assumptions and merely demonstrate that automatic processing is in fact possible.

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Timothy Payne received his B.Eng. with honours in Electronic Engineering in 1989 from the Royal Melbourne Institute of Technology, a B.S. in mathematics with distinction in 1990 from the Royal Melbourne Institute of Technology, and a Ph.D. in Electrical Engineering from the University of Adelaide in 1994. In 1990 he commenced work as an Electronic Engineer at DSTO.in the Surveillance Research Laboratory where he worked on control systems, image processing, laser power supplies and interfaces. He is currently employed as a Research Scientist in the Image Processing group of the Land, Space and Optoelectronics Division, Electronics and Surveillance Research Laboratory, DSTO, and is a member of the Cooperative Research Center for Sensor Signal Information Processing.
His research interests include data fusion, image processing, neural networks, and complex systems.

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Contents

1. Introduction

Long range oblique Electro Optic (EO) imagery represents a form of information gathering which is remote, controllable (assuming the weather cooperates) and reveals aspects of structure that are different from that of other remote information gathering processes, such as satellite or high altitude aircraft. The imagery is however difficult to analyse because its scale varies over the scene, and the objects within the scene will appear to be distorted and misplaced between two images taken from slightly different locations. The EO imagery considered in this report considers both visible and Infrared (IR) images.

SAR imagery, especially when taken from the large oblique angles considered in this report, produces an image which looks very much like a nadir view image. Consequently the features are easily associated with features on a map. The images have the advantage that resolution is constant with range from the sensor and that they are immune to the effects of cloud and smog; however the resolution is generally lower than that obtainable from an EO sensor and significant noise and clutter can occur.

This report contains an evaluation of what can be gained from the combination of oblique EO imagery and Synthetic Aperture Radar (SAR). This provides an approach where oblique EO and nadir images can be obtained simultaneously from the same platform. The implication of Digital Terrain Models (DTM) on this work is also discussed.

Section 2 discusses the procedures used in warping an oblique EO image to a nadir view, and explains how measurement of the camera and line of sight parameters allow this to be done automatically. Section 3 explains how the different perspectives obtained in the SAR and EO images, taken from the same platform, allow elevation information to be obtained. Section 4 presents the reverse situation to Section 3 where the elevation is known and can be used to correct the distortion in the image. Section 5 considers the combination of the SAR and the oblique EO image. The extraction of a DTM, the structure of buildings and the improved classification possible from the combined information are all discussed. Section 6 discusses the advantage of representing information in a 3D form rather than as a 2D representation which is subject to perspective differences in different images of the same scene. Section 7 briefly discusses some resolution issues which arise from the use of two sensors with different resolutions. Finally some recommendations for future work are given.

2. Remapping Long Range Oblique Images

Analysis of long range oblique aerial images (see Figures 9, 12 and 13 in Appendix B) is difficult since the scale of the information varies across the image, making it difficult to compare structures in different parts of the image or to determine the geographical association of objects; however a transformation can be applied to the image to equalise the scale of the detail and register the image on a range-azimuth projection (see Figure 10, 14 and 15 in Appendix B). In the oblique imaging situation the range-azimuth projection provides substantially the same information as would be available from a nadir view of the scene (see Section 3). The scale equalisation applied to the oblique EO image to form the range-azimuth projection makes the determination and measurement of information in the scene simple.

The transformation can be determined precisely if knowledge of the imaging parameters and some information about the scene is known. The resultant image has the disadvantage that elevation information is smeared in the range direction. If the elevation is known then this smearing can be eliminated; however this will leave portions of the image blank since they were obscured by the objects, which were smeared in range, from the EO sensor. Alternatively if the true location of objects is known, then the elevation of the objects can be determined.

The transformation of the image to a range-azimuth projection occurs by remapping the pixels in the original image. The transformation is nonlinear but is relatively simple to obtain since it can be derived from the camera and line of sight parameters at the time the image was acquired. The optical image is represented by a grid of square pixels in the horizontal (indexed by x) and vertical (indexed by y) directions. Each pixel represents the scene in an arc of azimuth and elevation from the camera; however, although the pixel grid is uniform the elevation and azimuth viewed by each pixel is not.

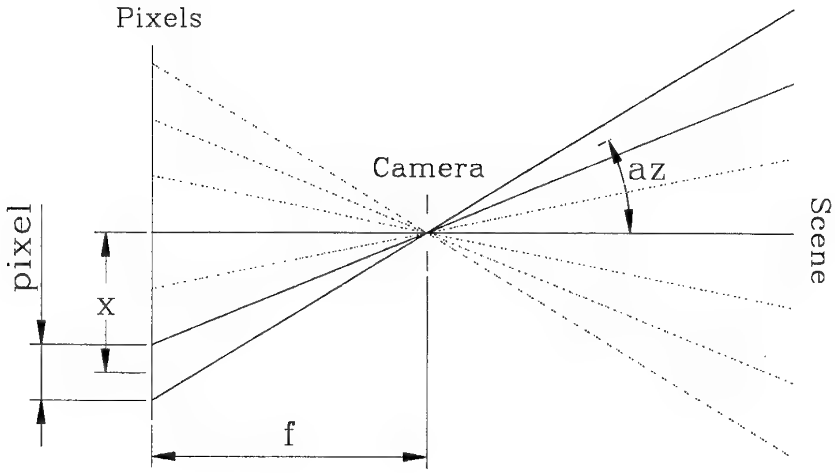

Figure 1: Relationship between pixel position and the azimuth viewed by each pixel.

The azimuth and elevation (Figure 1) relative to the optical axis of the camera can be calculated from

$$az = \tan^{-1}\left(\frac{x}{f}\right),$$

$$\text{and } el = \tan^{-1}\left(\frac{y}{f}\right),$$

where x and y are the horizontal and vertical distances in mm from the centre of the image in the imaging plane of the camera and f is the focal length of the camera in mm. To allow for rotation in the image plane (Figure 2) about the optical axis, the x and y positions are found from the pixel locations xp and yp, where the pixel origin is in the middle of the image.

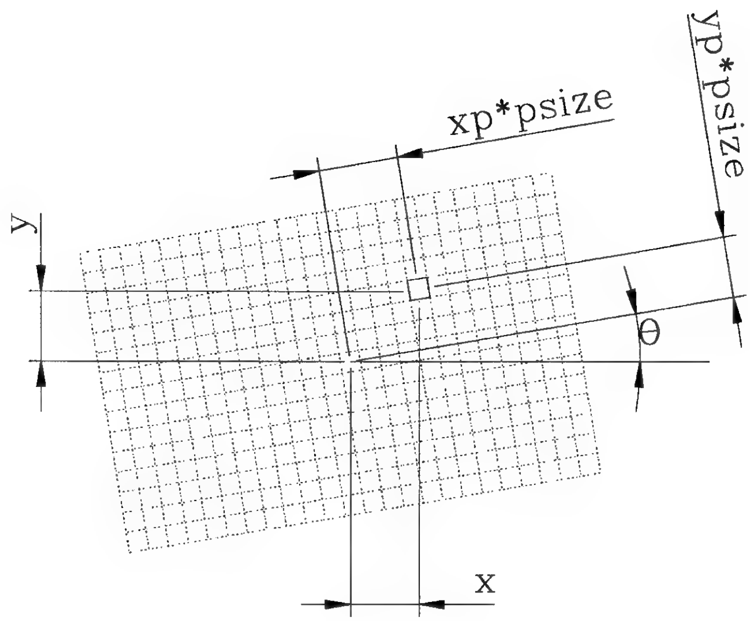

Figure 2: Correction for rotation about the optical axis.

$$\begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} xp * psize \\ yp * psize \end{bmatrix}$$

psize is the size in mm of each pixel in the focal plane of the sensor, and θ is the angle of rotation of the camera about the optical axis. * represents multiplication. To align the image with a global coordinate system, it is necessary to know from what point the image was obtained and the direction of the camera's optical axis.

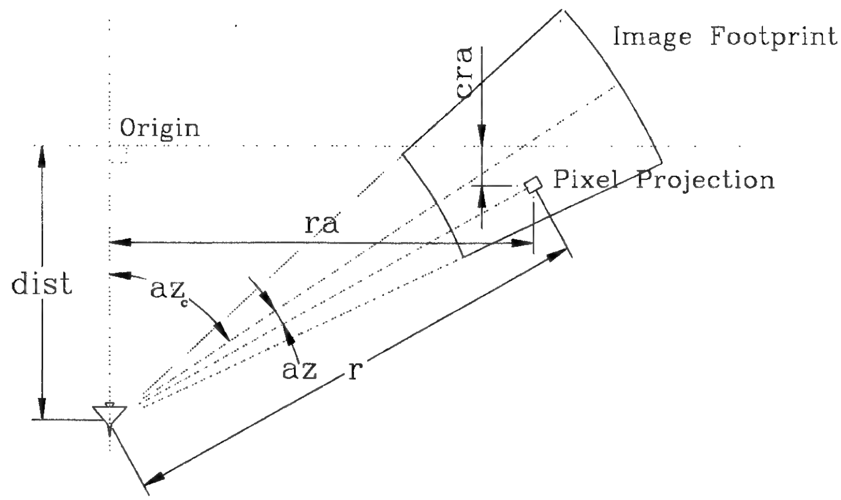

Figure 3: Projection of an Oblique EO scene on a Nadir view.

Images which have been mapped to a range-azimuth projection consist of pixels which are indexed by range and cross range. The range represents the distance of a pixel from the flight path of the aircraft measured along a line perpendicular to the flight path of the aircraft. The cross range represents the distance between the pixel and an origin point which is measured along a line parallel with the flight path of the aircraft (see Figure 3 and 4).

The range and cross range are calculated in the following manner

$$ra = r\sin(az_c + az)$$

$$cra = dist - r\cos(az_c + az)$$

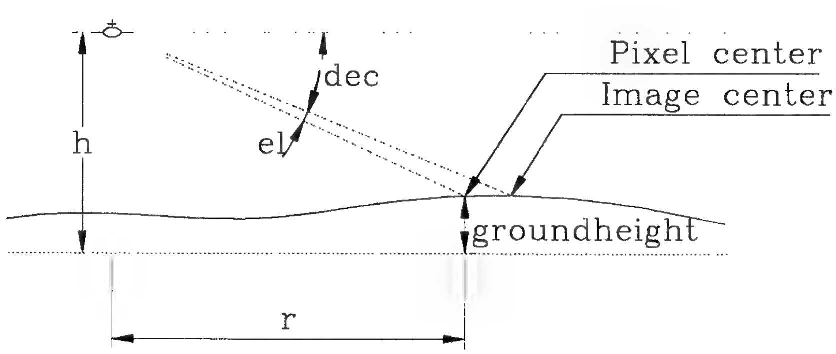

Figure 4: Determination of range, r, from height and angle information.

$$r = \frac{h - groundheight(ra, cra)}{\tan(dec - el)}$$

ra is the range from the flight path, *cra* is the cross range or distance from the origin parallel to the flight path (this consists of 2 parts, the distance the plane has travelled beyond the origin, *dist*, and a distance caused by camera pointing). az_c is the angle between the flight path and the direction in which the camera's optical axis was pointed, *dec* is the declination of the camera from the vertical, *h* is the height of the aircraft and *groundheight(ra, cra)* is the height of the ground, and any objects on it, at a particular range and cross range. In the distorted images above the *ground height* was not known and was assumed to be constant.

2.1. Determining Camera Measurements

It is often difficult to directly measure the parameters used in the above procedure and an analysis of the potential errors involved is performed in Appendix A. It is also possible to determine the parameters accurately after image acquisition but this requires higher level knowledge, and control points. Control points are features present within the image which are identifiable in both the EO image and the SAR, or another nadir view (another sensor, Digital Terrain Map (DTM)[1], map etc.). If the altitude of these identifiable control points is known, then the camera parameters can be determined by estimating and then iteratively modifying the parameters so that the magnitude of the error between the predicted location of the control points in the EO image calculated using the camera parameters, and their true location is minimised. The procedure of selecting control points can be performed manually in most scenes but will be difficult to do automatically in all situations. Unfortunately this technique is the only approach which will lead to sufficiently accurate camera parameters to register the images, or to determine additional information, such as height, to a precision approaching the resolution of typical EO systems.

3. Elevation Extraction Using SAR Information

The advantage of SAR as a surveillance system is that it offers an all weather standoff imaging system. Long range oblique EO imagery, although not an all weather system, can provide imagery at a high resolution and from different spectral bands, making classification of objects within the image simpler. The combination of information from the two sensors may offer some improvements over the independent systems. SAR images, just like EO images, produce shadows which enable the height of objects to be determined. This process is difficult since the recognition of shadows will be difficult

[1] A DTM is a digital map in which the elevation of the surface is represented at a grid of points.

and meaningless unless information is known about the ground over which the shadow is projected. The accuracy of this information will be equivalent to that of the SAR. Interferometric SARs[1] probably offer a better means of automatically determining height information than the fusion of EO and SAR; however the result will probably be less accurate than that obtainable with an EO sensor simply because of the high noise level in SAR images.

Combining the information from the two sensors is difficult because the images are different projections of the scene (see Figures 9 and 10). The two sensors, mounted on the same platform look at the same 3D scene and record the information as a 2D projection of that scene (Figure 5). The EO imagery records an azimuth and elevation projection, while the SAR records an azimuth and range projection. The SAR projection is at right angles to the projection of the EO sensor (Figure 5). An image with the same geometry as the SAR projection could have been obtained by placing an azimuth-elevation sensor at right angles to the original optical axis. The SAR image is slightly different to the image that would be produced by placing an EO sensor at the equivalent azimuth-elevation SAR projection point (see Figure 5), since the SAR detects all the surfaces that are illuminated and so detects surfaces which are hidden from the equivalent azimuth-elevation sensor but displays them as if they were visible from that point. ie. parts of the image which are not illuminated by the SAR appear transparent in the equivalent azimuth-elevation projection. The consequence of this is that although a stereo pair of images has been obtained, some of the problems caused by having to associate one side of an object in one image with another side of the object in the other image are avoided since both images show the same facets of objects, but from different projections.

The angle between views of the scene is large compared to standard stereo images. This has the advantage that high accuracy and resolution of depth is obtained but increases the difficulty in matching the two images together, since the disparity caused by elevation is large. The matching is also made more complicated because features and noise statistics may appear to be different in different parts of the electromagnetic spectrum.

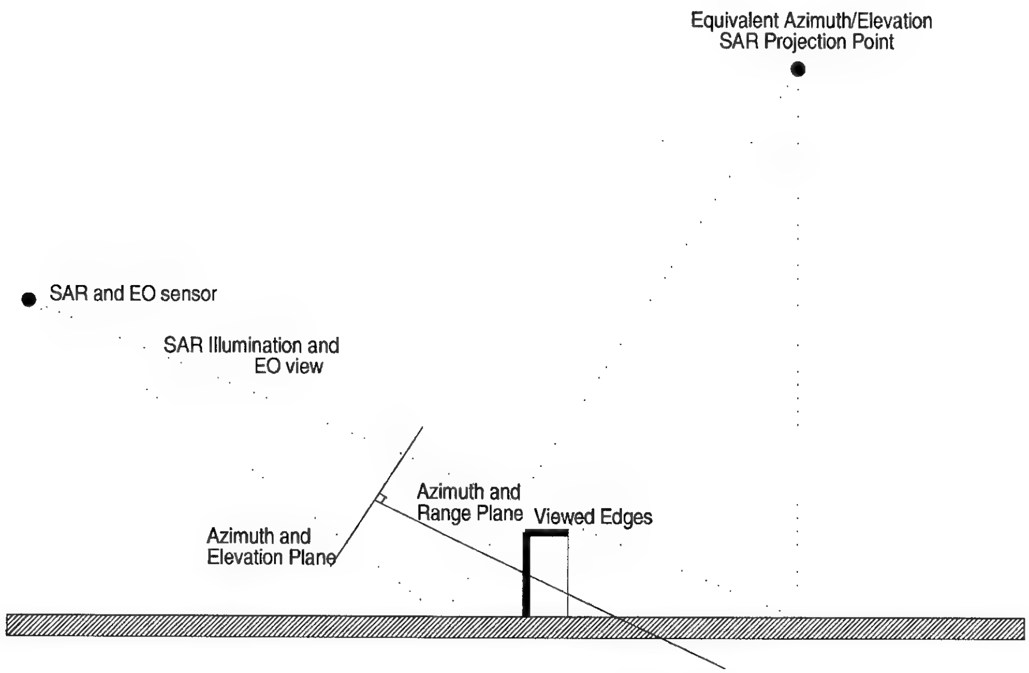

Figure 5: Effective views of a scene.

Mis-registration between a registered oblique EO image under the assumption that the *groundheight* is constant, and a nadir view image (such as SAR), can be directly attributed to the ground height[2]. From Figure 5 it can be seen that the building top appears in the oblique image at a greater elevation than the base; if it was assumed that the building was flat (as would be done when no information about the building was available) then the top of the building would be mapped to a point on the ground behind it. The change in the value of r, Δr, for the EO sensor compared to the true position (see Figure 4) can be expressed as

$$\Delta r = \frac{\Delta groundheight(ra, cra)}{\tan(dec - el)}$$

where $\Delta groundheight(ra, cra)$ is the difference between the assumed elevation of the building when performing the registration of the oblique EO to the SAR image and the actual elevation. The value that is obtained is not the height of the building but the

[2] Ground height is used to refer to the height of the ground above an arbitrary zero elevation plane (refer to Figure 4) or in the case where an object exists, such as a building, then ground height refers to the distance between the top of the building and the zero elevation plane.

distance between the zero elevation plane and the point of the building in the EO image used to perform the registration. To determine the height of the building the Δ*groundheight* for both the top and bottom of the building need to be determined. This range error appears in the image as a smearing of elevation into range[3]. Conversely if the smearing can be determined then the true ground height (height of the ground and the objects on it) can be calculated. The critical issue of matching points on both the EO and SAR images (which are required to calculate Δr) is discussed in Section 5.2.

4. Remapping Using DTMs

If a DTM is available then it is possible to remove the smearing in the range direction due to elevation. Once the scene has been corrected for elevation, the information from multiple sensors, which are also registered to the same nadir view, can be combined without the need for complicated high level matching procedures since structures which are at the same location on the ground will appear at the same coordinate in each sensor. It is unlikely that the resolution of the DTM will be such that the information about structures in the image will be included. This means that objects in the different images will be located at the same coordinate only at their bases, vertical structures will still be smeared in the range direction of the image, but this is not necessarily a problem since much of the information which can be obtained from an oblique EO image is this vertical structure.

It should be noted that DTMs are not available, or do not exist at an adequate resolution, in many areas of interest at the moment, and indeed may not in the future. A common accuracy currently for a DTM in Australia is 10m, yet to be of use the error in the DTM should be less than the elevation of a pixel in the oblique image. This is less than 1m in most imaging systems that would be used to extract the type of information being sought. In situations where the local relief was significantly greater than the error in the DTM then there is still some value in correcting using the DTM, since this provides a coarse registration of the images; however in this situation a dense grid of digital elevations is required.

The use of a DTM to correct registration to allow for perspective variations in the imagery would allow the association procedure between sensors to be automated, since objects would appear at the same location; however, the existence of DTMs at the

[3] It should be noted that the elevation of either the top or bottom of the building can be determined to an accuracy controlled by the least accurate of the SAR and EO sensors, the differential accuracy is controlled by the EO sensor alone since the top and bottom of the building will appear at the same location in the SAR image so that when the elevation of the bottom of the building is removed from the top, the error caused by the SAR cancels, leaving only the error caused by the EO sensor, which in general will be more accurate than the SAR. Appendix A2 discusses the resultant errors that will occur in this procedure.

required accuracy is unlikely and means that correction with a DTM can provide little more than a coarse registration.

5. SAR And Oblique EO Image Fusion

Long range EO imagery provides a great deal of information to an analyst, yet the capture of this information is subject to the weather, in particular clouds. SAR on the other hand provides less detail but will work in all weather conditions. SAR is also very good at picking out man made features. A dual sensor system consisting of SAR and EO sensors will therefore provide information when for one reason or another the other sensor does not work; however, more information is available when the information from the sensors is combined. Three types of information which may be deduced from fusion of SAR and oblique EO imagery are discussed in this section - extraction of a DTM, structure extraction after elevation correction, and improved classification.

5.1. Extraction of a DTM

If there is no DTM available then the mis-registration of the SAR and the oblique EO image gives the elevation of features which can be uniquely identified in the two images. In all but the simplest cases an automatic procedure for uniquely matching features in the two images is difficult (see Section 5.2); however it can generally be performed manually without difficulty. An exception, where automated procedures will work, is in a scene with only a few easily identifiable objects, such as trees or road intersections, which can be automatically detected in both sensors. If the objects are too sparse, then the elevation of only a few points can be determined, if the objects are too close, then it will become difficult to automatically associate a point from one image uniquely with a point from the other image.

Elevations can thus be determined at a number of points through out the image and other points can be interpolated between these points, allowing most of the smearing, due to elevation, to be removed. Some features with elevation, such as buildings, will remain smeared since it is not possible to find a one to one association between points in the images. The vertical facets of buildings and such structures are smeared in the EO image producing multiple features, while in the SAR image, because the facet is vertical, all those features occur at approximately the same range and consequently overlap. The result is a many to one association. A method for determining the elevation of these types of structures is presented in the next section. It is assumed that the correction determined in this section has been applied so that the bases of these vertical structures are positioned at the correct range. The determination of DTMs is

probably more easily determined using an interferometric SAR so more work in this area has not occurred.

5.2. Structure Extraction after Elevation Correction using SAR and EO

It is possible, by analysing an oblique EO image, to extract information about the size and shape of objects in the scene. This can be carried out by recognising the type of object and the way in which the geometry of the imaging will depict that object. i.e. recognising an object as a building, as opposed to a road, changes the meaning attributed to distance in the picture. Both distances are measured along the same axis; however, since we know which edges are vertical and which are horizontal, the scale applied to different edges will vary. Automation of this process to extract structure is difficult since objects within the scene need to be classified first and then fitted to a model of that structure to determine whether facets of the object are vertical, or horizontal, so that the dimensions can be determined. In a situation where large simple buildings are of interest, fitting models to objects within the scene can be performed relatively simply, but the existence of small vertical objects such as posts, towers, small buildings, and complex objects such as buildings on wharfs, would make this approach difficult, so an alternative has been sought.

An alternative to fitting models to the scene, is possible when the additional information from a SAR image is available. The oblique EO sensor determines the existence of facets by detecting the boundaries of uniform regions. The SAR image enables us to determine the slope of some of the facets, since horizontal to rising vertical facet boundaries produce a strong return, while horizontal facets produce a much lower response (this can be seen in Figure 11 with the buildings around the wharf). The SAR information needs to be matched to the information in the EO image if it is to be used. In the following example the oblique EO image has already been distorted so that the ground is registered to the SAR image, this means that matching is simple because the base of objects will occur at the same range and crossrange in the SAR and registered EO image. Structures with elevation within the EO image are still smeared in range; the determination of their structure will enable this smearing to be removed.

It is assumed that different facets of a building would be separated by a discontinuity in the intensity map in the EO image. The transition from a horizontal surface to a vertically rising facet of a building produces a line in the SAR image, while other transitions will probably produce little effect. Structures with vertical faces such as buildings were also assumed to have the same shaped edge at the top of the vertical face and at the bottom. (ie. vertical faces are rectangles) Figure 6 shows an example of a building's facets as seen in a registered oblique EO image (top), the same building as seen by a SAR sensor (shown beneath the EO image - note that only the leading bottom

edges are visible), and the cross section of the building after reconstruction. The images in Figure 6 were acquired from the left side of the page, where the aircraft is shown, so range is measured from left to right, and cross range from the top to the bottom of the page. The different facets of the buildings are identified from the EO scene by their different colours. In the SAR image of the equivalent scene, only the bottom left facing edges can be seen.

Discontinuities in the EO image gradient reflect a change in the angle of the reflecting surface. Facet edges, within the oblique optical scene, which have a component perpendicular to the line of sight are determined by differentiating the intensity along each line of pixels in the range direction (from left to right in Figure 6). By scanning the EO and SAR images along a line of pixels which have the same cross range, ie. from left to right in Figure 6, the bottom edge of vertical facets of buildings will be revealed when the line of pixels being scanned cross a line in the SAR image and a facet edge indicated by a discontinuity of the intensity in the EO image ('First Edge' in Figure 6). The end of the vertical facet will be the next discontinuity encountered in the EO image ('Second Edge' in Figure 6) and the next facet will be horizontal. This horizontal facet continues until another discontinuity is detected ('Third Edge' in Figure 6) which represents the opposite edge of the building.

To improve the performance of the above approach and to prevent spurious edges from being used for the second and third edges of a building, which would generate false structure information, the selection of the second and third edges is constrained to discontinuities in the EO image which are parallel. This is true for rectangular buildings (refer to the cross section line C-D in Figure 6) except near the edges (refer to the cross section line A-B in Figure 6) where it is still true for the second edge; however the horizontal top facet of a building may have front (second edge) and back edges (third edge) on the same cross range line which are perpendicular.

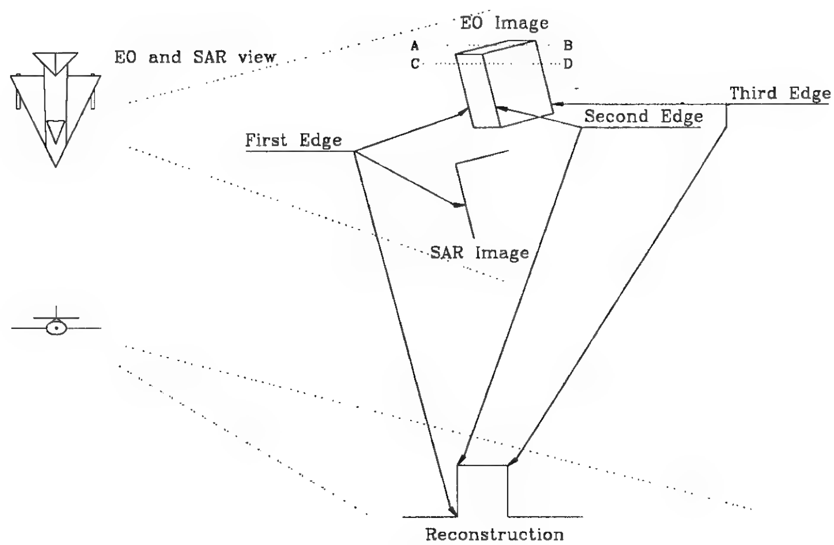

Figure 6: Matching of edges in the SAR, EO and Reconstructed object.

This simple procedure is capable of determining the size and position of simple buildings in a scene. By adding thresholds, and matching edges which are parallel, so that only significant edges are detected the process will also work with small amounts of additive noise. With increased amounts of noise the procedure will periodically miss an edge or generate another edge which makes all successive facets incorrect. By limiting the potential size of buildings to a reasonable size this kind of error can be detected and the process can be placed back on track.

This procedure could be improved markedly by incorporating additional knowledge about the expected shape of objects; however, this would mean that the analysis would become more and more specialised as its performance improved.

To illustrate the operation of the structure extraction procedure a simulation was performed with a simple scene consisting of a number of buildings. The registered oblique EO image and the SAR image are shown in Figure 7. Illumination of the EO image is coming from behind the aircraft, and a simple reflectance model has been utilised to determine the color of the facets. Because the illumination source is coming from behind the aircraft, shadows from the buildings are obscured. The first subfigure in Figure 7 represents the simulated registered oblique EO scene with additive white gaussian noise, the second is the SAR image with noise (the noise has a Weibull distribution [2]).

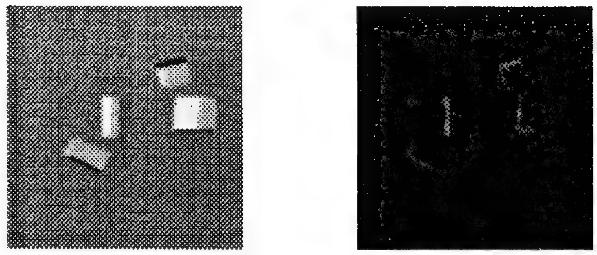

Figure 7: Simulation of structure extraction, registered oblique EO image, and SAR image.

Figure 8 contains two images, the first depicts the elevation which was derived using the above mentioned procedure, with an intensity corresponding to the elevation, at each point in the EO image. The height of an object in the EO image can be determined by examining the intensity of the corresponding pixel in the elevation image. The second subfigure in Figure 8 represents the unsmeared EO image determined using the calculated elevation information. This final image shows where the mapping has and has not been successful. In particular the procedure has failed at the corners of buildings where the edges of the top facet on the same horizontal line (line of constant cross range) are not parallel but perpendicular, since they correspond to adjacent edges, not opposite edges as assumed. Where the mapping has been performed successfully only the tops of buildings should appear since their vertical faces are not seen from above. The approach has generated the correct height of all the buildings, in particular the top three buildings have had almost all the smearing in range removed. Because of the orientation of the lowest building, the third edge is almost always perpendicular to the first two edges, so the elevation of the vertical sides has been determined accurately (and mapped to a line in the second subfigure of Figure 8 as required) but the horizontal roof of the building has not been determined.

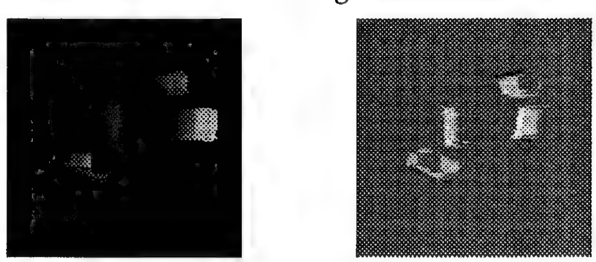

Figure 8: Results of structure determination using information from Figure 7. Elevation of points in the oblique EO image, and the resultant image after the smearing in range, caused by the object's structure, has been removed.

5.3. Classification after Elevation Correction using SAR and EO

Whether the oblique EO image is elevation corrected using a DTM, or whether features have been matched to form a DTM which has then been used to correct the image is unimportant. After elevation correction the SAR and EO images should be registered. The smearing in range of vertical structures need not be corrected since the region concealed by the smearing corresponds to a region of shadow in the SAR image. The two registered images can be used as inputs to a classifier to increase the information available for decision making processes, thus improving the classification performance of a single sensor alone.

The two sensor systems once registered provide different information which would make classification of objects in the scene easier. SAR is good at picking man made objects from natural objects and could at the very worst draw attention to man-made objects within an optical scene.

Clement et. al. [3], Wong and Orth [4], Liu et. al. [5] and JPL Pasadena [6], have demonstrated that it is possible to successfully register SAR images with multispectral data, and that the results obtained are beneficial for the purpose of classification and analysis; however in the above examples registration required the manual extraction and matching of control points from the two images.

6. Difference Detection After Elevation Correction Has Occurred

In the normal mode of operation the effective azimuth-elevation projection of the SAR is similar to a nadir view, particularly for relatively flat scenes as is common in a large portion of remote Australia. Because the view is almost a nadir view, images taken at different times from slightly different locations will appear to have the same geometry (ie. objects will not appear to be distorted between the scenes). Objects in EO images are far more sensitive to elevation than objects in a SAR image, and so images of objects taken from slightly different locations, will be distorted and located in different positions within the scene, in all but perfectly flat terrain, making the detection of change between two images almost impossible. If a SAR and an oblique EO image are captured simultaneously and it is possible to associate objects in the SAR with objects in the EO imagery, then the distortion in the oblique EO image caused by the terrain can be removed and the EO image can be aligned with other EO images captured at different times so that difference detection can occur. This procedure is superior to undistorting images using a DTM, because the resolution of DTMs is low, and the elevation information, at least at the moment, is only known on a sparse grid. Features in the EO image can be corrected using the DTM but the correction suffers because of low accuracy in the DTM values and from interpolation errors between the DTM grid

points, whereas if the elevation is corrected using a simultaneously acquired SAR image then the objects of interest, which are seen by each sensor, can be located at the precision of the sensors, allowing the object and its location to be compared between images at different times.

7. Resolution Issues

Until this point a discussion of resolution has been avoided, so as not to further complicate the previous discussions. In general the EO sensor will have a higher resolution than the SAR sensor, but the issue is not that simple either. If the EO sensor has square pixels then the projection on the ground of each pixel will be far from square so that the resolution in the range and cross range will be different. In the example images presented the range resolution of the EO projection was the same as the range resolution of the SAR, while the cross range resolution was much higher than in the SAR. Different SAR products (such as a single look image) would, however, have a different cross range resolution.

In registering and displaying the images it is necessary to either reduce the resolution of some of the image components, or to increase the resolution of other image components by interpolating so that the range and cross range resolution of all the images are identical. The result of course is to either destroy information or to generate much larger images which may then result in storage difficulties.

The consequence of the various resolutions is that elevation information obtained from the fusion of the images will have a different resolution depending upon the mechanism by which the information was extracted. By matching a feature in the SAR and the EO image height is determined which has a resolution which is a function of the resolution of the SAR range resolution and the projected EO range resolution, while if the height is determined from range smearing in the EO sensor then the height resolution is close to the elevation resolution of the EO sensor rather than the projected range resolution.

8. Conclusion

Elevation information can be obtained by fusing a SAR and an oblique EO image - this information cannot be obtained from either of the sensors individually. Unfortunately this information requires objects within the images to be identified uniquely, and with the exception of some simple scenes it is unlikely that this identification problem can be solved automatically. In the situations where an automatic solution is possible it may still be more efficient to perform the operation manually given the effort required

to set up the automation procedure and the limited versatility and area of applicability of the automation.

The registration of the oblique EO image to a plan map or other sensor is certainly of significance to aid in the use of several sources of information, since it means that the information appears the same, and less time need be spent looking for the corresponding information from the multiple sources. Unfortunately, measuring the camera and line of sight parameters to perform this operation is not a simple task and registration may need to be done by the detection of control points with a known elevation.

For oblique EO and SAR information to be fused to improve classification, accurate registration which takes into account the height of features in the scene must occur. Since DTM are not available at the appropriate resolutions the elevation of features must be determined manually. The question needs to be raised, whether the effort in registering the images is greater than that required for manual analysis and classification.

The fusion of SAR and oblique EO images is useful as an intelligence gathering tool which will enable users to remove distortions from oblique images and determine any structural changes in the scene which may have occurred between the acquiring of the EO images, such as the movement or change in size of objects.

The extraction of elevation information is also possible; however this process will be difficult to automate and is consequently not a viable method of determining elevations over a large area.

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Appendix A

Calculations.

A1 Derivation of Registration Errors

The errors in range and cross range caused by small errors in determining the position and orientation of the camera are approximated by the following expressions,

$$\Delta ra \approx \Delta az_c \frac{\partial ra}{\partial az_c} + \Delta\theta \frac{\partial ra}{\partial \theta} + \Delta dec \frac{\partial ra}{\partial dec} + \Delta h \frac{\partial ra}{\partial h}$$

$$\Delta cra \approx \Delta az_c \frac{\partial cra}{\partial az_c} + \Delta\theta \frac{\partial cra}{\partial \theta} + \Delta dec \frac{\partial cra}{\partial dec} + \Delta h \frac{\partial cra}{\partial h}$$

$$\begin{aligned}\frac{\partial ra}{\partial az_c} &= r\cos(az_c + az) \\ &= dist - cra\end{aligned}$$

$$\begin{aligned}\frac{\partial cra}{\partial az_c} &= r\sin(az_c + az) \\ &= ra\end{aligned}$$

$$\begin{aligned}\frac{\partial ra}{\partial \theta} &= \frac{\partial r}{\partial \theta}\sin(az_c + az) - r\frac{\partial az}{\partial \theta}\cos(az_c + az) \\ &= \frac{\partial r}{\partial el}\frac{\partial el}{\partial y}\frac{\partial y}{\partial \theta}\sin(az_c + az) + \frac{\partial az}{\partial x}\frac{\partial x}{\partial \theta}(cra - dist) \\ &= \frac{-rfx\sin(az_c + az)}{(f^2 + y^2)\sin(dec - el)\cos(dec - el)} + \frac{fy(cra - dist)}{f^2 + x^2}\end{aligned}$$

$$\begin{aligned}\frac{\partial cra}{\partial \theta} &= -\frac{\partial r}{\partial \theta}\cos(az_c - az) - r\frac{\partial az}{\partial \theta}\sin(az_c + az) \\ &= -\frac{\partial r}{\partial el}\frac{\partial el}{\partial y}\frac{\partial y}{\partial \theta}\cos(az_c + az) - \frac{\partial az}{\partial x}\frac{\partial x}{\partial \theta}ra \\ &= \frac{rfx\cos(az_c + az)}{(f^2 + y^2)\sin(dec - el)\cos(dec - el)} - \frac{fyra}{f^2 + x^2}\end{aligned}$$

$$\frac{\partial ra}{\partial dec} = \frac{\partial r}{\partial dec}\sin(az_c + az)$$
$$= \frac{-r\sin(az_c + az)}{\sin(dec-el)\cos(dec-el)}$$
$$\frac{\partial cra}{\partial dec} = -\frac{\partial r}{\partial dec}\cos(az_c + az)$$
$$= \frac{r\cos(az_c + az)}{\sin(dec-el)\cos(dec-el)}$$

$$\frac{\partial ra}{\partial h} = \frac{\partial r}{\partial h}\sin(az_c + az)$$
$$= \frac{\sin(az_c + az)}{\tan(dec-el)}$$
$$\frac{\partial cra}{\partial h} = -\frac{\partial r}{\partial h}\cos(az_c + az)$$
$$= -\frac{\cos(az_c + az)}{\tan(dec-el)}$$

$$\therefore \Delta ra \approx \Delta az_c(dist - cra) + \Delta\theta\left(\frac{-rfx\sin(az_c + az)}{(f^2+y^2)\sin(dec-el)\cos(dec-el)} + \frac{fy(cra-dist)}{f^2+x^2}\right)$$
$$+\Delta dec\left(\frac{-r\sin(az_c + az)}{\sin(dec-el)\cos(dec-el)}\right) + \Delta h\left(\frac{\sin(az_c + az)}{\tan(dec-el)}\right)$$

$$\therefore \Delta cra \approx \Delta az_c(ra) + \Delta\theta\left(\frac{rfx\cos(az_c + az)}{(f^2+y^2)\sin(dec-el)\cos(dec-el)} - \frac{fyra}{f^2+x^2}\right)$$
$$+\Delta dec\left(\frac{r\cos(az_c + az)}{\sin(dec-el)\cos(dec-el)}\right) + \Delta h\left(\frac{\cos(az_c + az)}{\tan(dec-el)}\right)$$

Since *cra* and *ra* are large compared to the other parameters in the above expression the error in *ra* and *cra* (Δra and Δcra) will be particularly sensitive to errors which are multiplied by *ra* or *cra*. In particular Δra and Δcra are extremely sensitive to the angular measurement errors Δaz_c, $\Delta\theta$ and Δdec in the long range oblique system under investigation. For example, if the resolution of the imaging sensor is 1m and the range is approximately 30km then it is required that the measurement error, Δaz_c, be less than 1/30000 radians (~33μrad), if the cross range estimate is to be comparable to the sensor resolution. The accuracy of this measurement would be difficult and unrealistic

to obtain; however, there are some potential solutions to the problem which are outlined in Section 2.1.

Although it is possible to determine the relative position of the EO sensor to the SAR, particularly if they are mounted on the same stabilising platform (stabilisation of EO platforms to 17μrad is possible), the errors will effect the two sensors in different ways. For example since the SAR measures range and azimuth, the errors Δaz_c, $\Delta\theta$ and Δdec will not affect the range or cross range positions of objects with in the scene. The appearance and resolution of the SAR image may be altered but the location of objects in the scene will not be altered.

A2 Derivation of Height Estimation Errors

Although the absolute value of the camera parameters cannot be determined to a sufficient accuracy to allow the determination of the correct range and cross range positions in the image, the question remains over whether the parameters are well enough known that the relative positions of objects in the scene can be determined. To determine the height of an object, such as a building, it is necessary to know the different ranges at which the top and bottom of the object appear.

The errors involved are analysed below and it is found that the error is approximately proportional to the height of the object. These errors are lower than the errors in the absolute values of range and cross range; however for large objects the error may still be significant.

$$\begin{aligned}\Delta height &\propto \Delta ra_1 - \Delta ra_2 \\ &= \Delta az_c\left(\frac{\partial ra_1}{\partial az_c} - \frac{\partial ra_2}{\partial az_c}\right) + \Delta\theta\left(\frac{\partial ra_1}{\partial\theta} - \frac{\partial ra_2}{\partial\theta}\right) + \Delta dec\left(\frac{\partial ra_1}{\partial dec} - \frac{\partial ra_2}{\partial dec}\right) + \Delta h\left(\frac{\partial ra_1}{\partial h} - \frac{\partial ra_2}{\partial h}\right)\end{aligned}$$

$$\frac{\partial ra_1}{\partial az_c} - \frac{\partial ra_2}{\partial az_c} = (r_1 - r_2)\cos(az_c + az)$$

$$\begin{aligned}\frac{\partial ra_1}{\partial\theta} - \frac{\partial ra_2}{\partial\theta} &= fx\sin(az_c + az)\left(\frac{r_2}{(f^2 + y_2^2)\sin(dec - el_2)\cos(dec - el_2)}\right. \\ &\qquad \left. - \frac{r_1}{(f^2 + y_1^2)\sin(dec - el_1)\cos(dec - el_1)}\right) + \frac{f(cra - dist)}{f^2 + x^2}(y_1 - y_2) \\ &\approx \frac{x\sin(az_c + az)}{f\sin(dec - el)\cos(dec - el)}\left(r_2 - r_1\right) + \frac{(cra - dist)}{f}(y_1 - y_2)\end{aligned}$$

since

$$\frac{f}{f^2+x^2} \approx \frac{f}{f^2+y^2} \approx \frac{1}{f} \text{ and } \sin(dec-el_2)\cos(dec-el_2) \approx \sin(dec-el_1)\cos(dec-el_1)$$

for small structures

$$\begin{aligned}\frac{\partial ra_1}{\partial dec} - \frac{\partial ra_2}{\partial dec} &= \sin(az_c + az)\left(\frac{r_2}{\sin(dec-el)\cos(dec-el)} - \frac{r_1}{\sin(dec-el)\cos(dec-el)}\right) \\ &\approx \frac{\sin(az_c + az)}{\sin(dec-el)\cos(dec-el)}(r_2 - r_1)\end{aligned}$$

$$\begin{aligned}\frac{\partial ra_1}{\partial h} - \frac{\partial ra_2}{\partial h} &= \sin(az_c + az)\left(\frac{1}{\tan(dec-el_1)} - \frac{1}{\tan(dec-el_2)}\right) \\ &\approx \frac{\sin(az_c + az)}{h}(r_1 - r_2)\end{aligned}$$

since $\frac{1}{\tan(dec-el_1)} \approx \frac{r_1}{h}$

$$\begin{aligned}\therefore \Delta height \propto\ & \Delta az_c\big((r_1 - r_2)\cos(az_c + az)\big) + \Delta\theta\left(\frac{x\sin(az_c + az)}{f\sin(dec-el)\cos(dec-el)}(r_2 - r_1)\right. \\ & \left. + \frac{(cra - dist)}{f}(y_1 - y_2)\right) + \Delta dec\left(\frac{\sin(az_c + az)}{\sin(dec-el)\cos(dec-el)}(r_2 - r_1)\right) \\ & + \Delta h\left(\frac{\sin(az_c + az)}{h}(r_1 - r_2)\right) \\ \approx\ & \Delta az_c\, k_{az}(r_1 - r_2) + \Delta\theta\, k_\theta(r_1 - r_2) + \Delta dec\, k_{dec}(r_1 - r_2) + \Delta h\, k_h(r_1 - r_2)\end{aligned}$$

assuming that $(y_1 - y_2) \propto (r_1 - r_2)$.

The above expression shows that the error in the estimation of the height of an object is approximately proportional to the height of the object, since the height of an object results in a different range between the base and the top. The proportionality constant is difficult to evaluate, and varies over a scene, but typical values for k are less than 1.

Appendix B

Images.

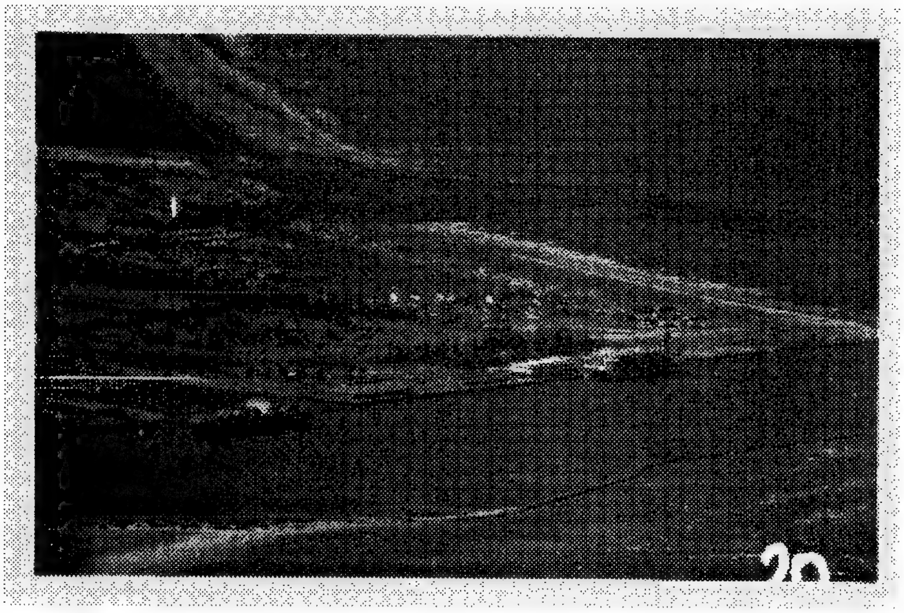

Figure 9: Oblique image of a region near Port Adelaide.

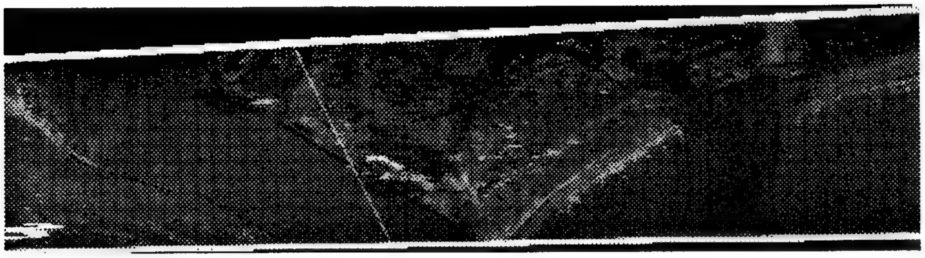

Figure 10: Transformed oblique image from Figure 9. (registered to Figure 11)

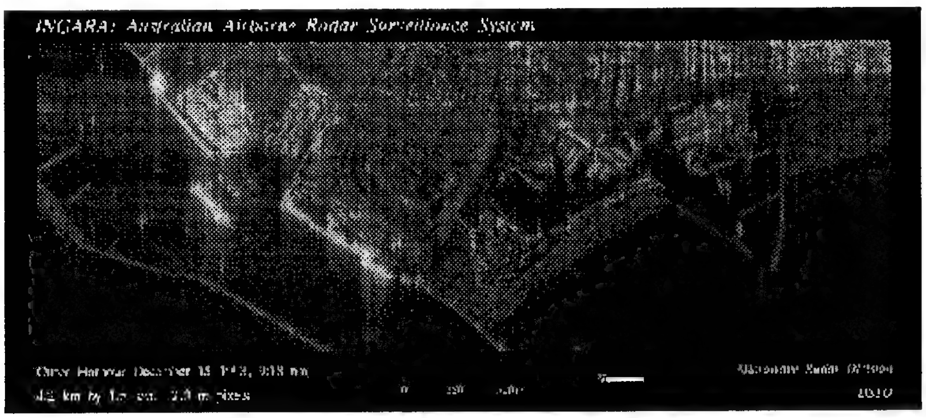

Figure 11: SAR image of the same region as Figure 9 and 10.

Figure 12: Oblique image of a region near Edinburgh airbase.

Figure 13: Oblique IR image of a region near Edinburgh airbase.

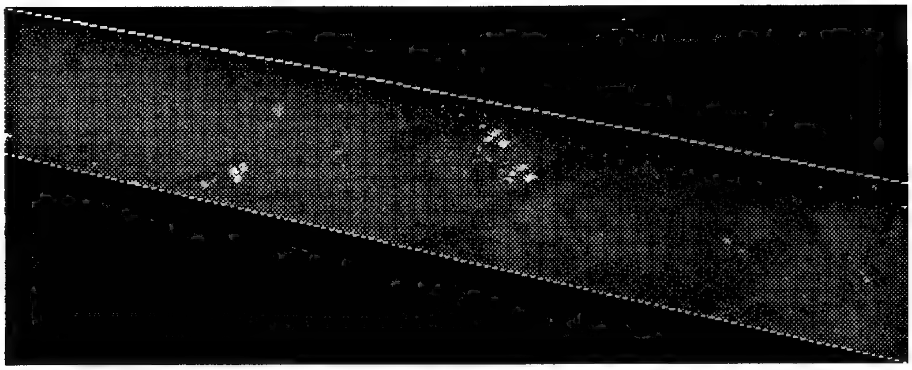

Figure 14: Transformed oblique image from Figure 12. (registered to Figure 16)

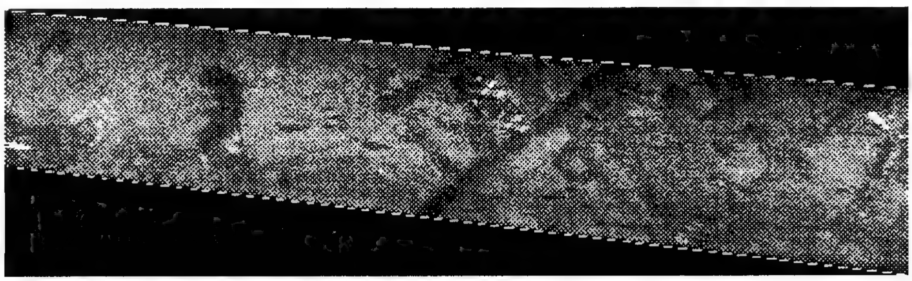

Figure 15: Transformed oblique IR image from Figure 13. (registered to Figure 16)

Figure 16: SAR image of the same region as Figure 14 and 15.

Appendix C

Proposed Future Work.

It is possible to determine the size of objects in an oblique EO image if we already know what the structure of the object is and the way in which different parts of the object will appear. The human brain is able to examine these oblique images and determine the size and shape of objects since we can also usually determine what the objects are. For this process to be automated the task is somewhat harder; however, if the range of objects of interest is reduced, and additional clues are provided, then the task becomes more manageable.

It is proposed to use images obtained from a SAR and an oblique EO sensor to determine the size, structure and position of objects on the ground. This procedure will involve several well defined steps:

1. Approximate flat earth registration. Using an assumption that the earth is flat and knowing the camera parameters, distort an oblique EO image to align with a SAR image.

2. Process images to extract features.

3. Identify objects, i.e. man made objects should be clearly visible in the SAR image.

4. Match features in the two images. i.e. lines in the same location of the same length and orientation are probably caused by the same feature.

5. Infer structure from matched features and probable hypothesis about object type. i.e. A building has only a limited number of possible structures, the matching of features should allow the other features to be easily determined.

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Timothy M. Payne

(DSTO-TR-0117)

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19. Abstract
The process of registering oblique EO imagery simultaneously acquired from the same platform as a SAR image is reported along with the usefulness of such information. The geometry of the images is different, and the process of warping the oblique EO image to the nadir or plan map type view of the SAR leads to information about elevations within the scene which cannot be obtained from either of the individual sensors without the inclusion of either prior knowledge of the scene or recognition capabilities.